Status and Future Plan of the Spectroscopy of Pionic Atom

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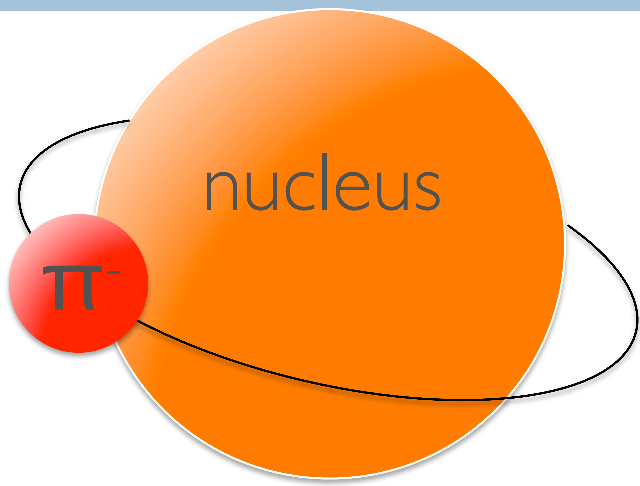
Contents

1. Introduction

2. Experiment at RI Beam Factory (RIKEN)
   -Pilot Experiment
3. Spectroscopy by Inverse Kinematics
   -Design of Experiment
4. Summary

Introduction: Deeply Bound Pionic Atoms



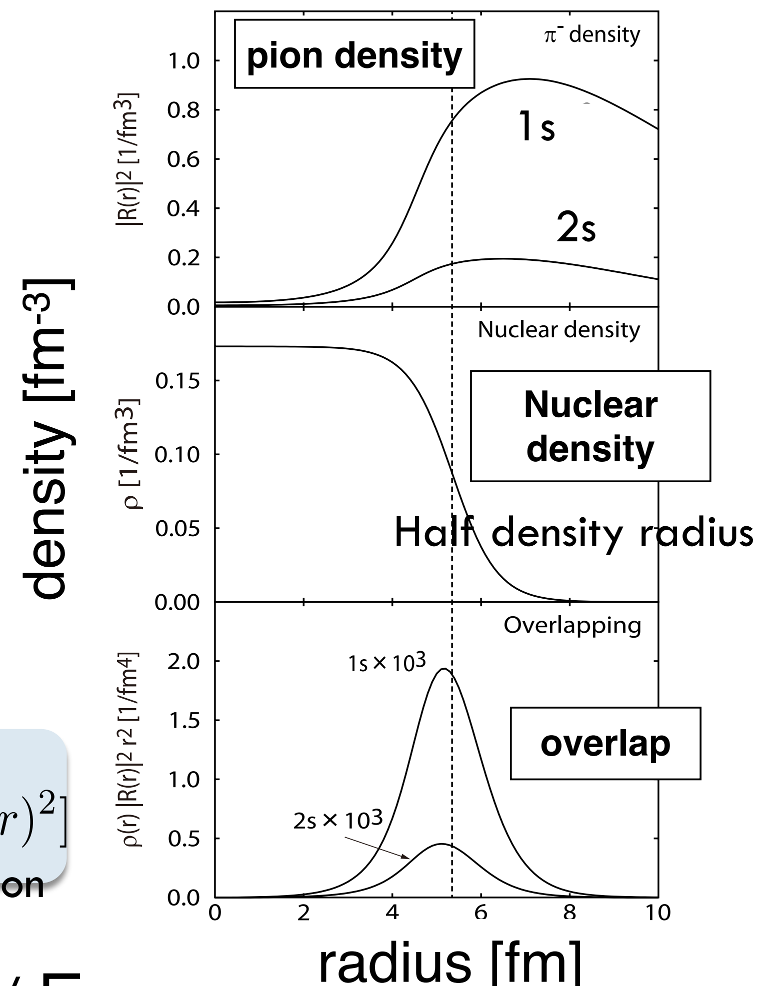
Interaction

EM

+

Strong

Pionic atom with ^{121}Sn



N. Ikeno *et al.*, PTP126(2011)483.

Large overlap!

→probe for QCD in finite density

strong interaction potential

$$V_s(r) = -\frac{2\pi}{\mu}[\epsilon_1\{b_0\rho(r) + b_1(\rho_n(r) - \rho_p(r))\} + \epsilon_2 B_0 \rho(r)^2]$$

absorption

Important!

B.E. / Γ

Physics Motivation: Chiral Symmetry Restoration

Tomozawa-Weinberg relation

$$b_1 = -\frac{m_\pi}{8\pi f_\pi^2}$$

Gell-Mann-Oaks-Reinner relation

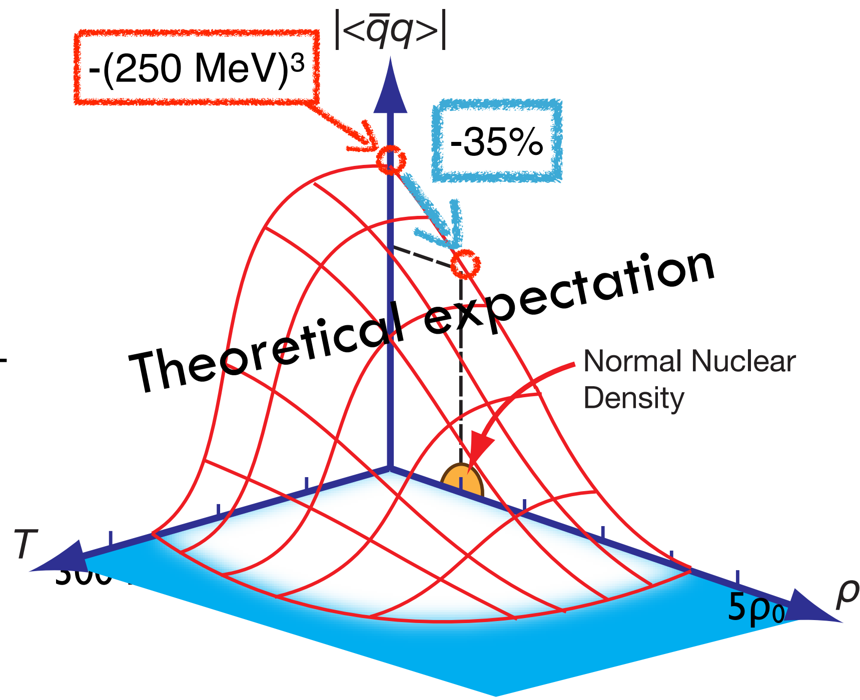
$$f_\pi^2 m_\pi^2 = -2m_q < \overline{q}q >$$

$$b_1 \propto 1/|\langle \overline{q}q \rangle|$$

In-medium $\rho = 0.6\,\rho_0$

$$\frac{b_1^{free}}{b_1^*} = \frac{|\langle \overline{q}q \rangle|^*}{|\langle \overline{q}q \rangle|^{free}}$$

In-medium $\rho = 0.6\,\rho_0$

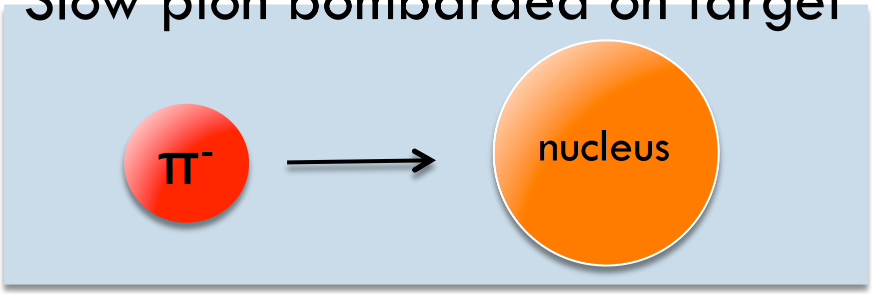


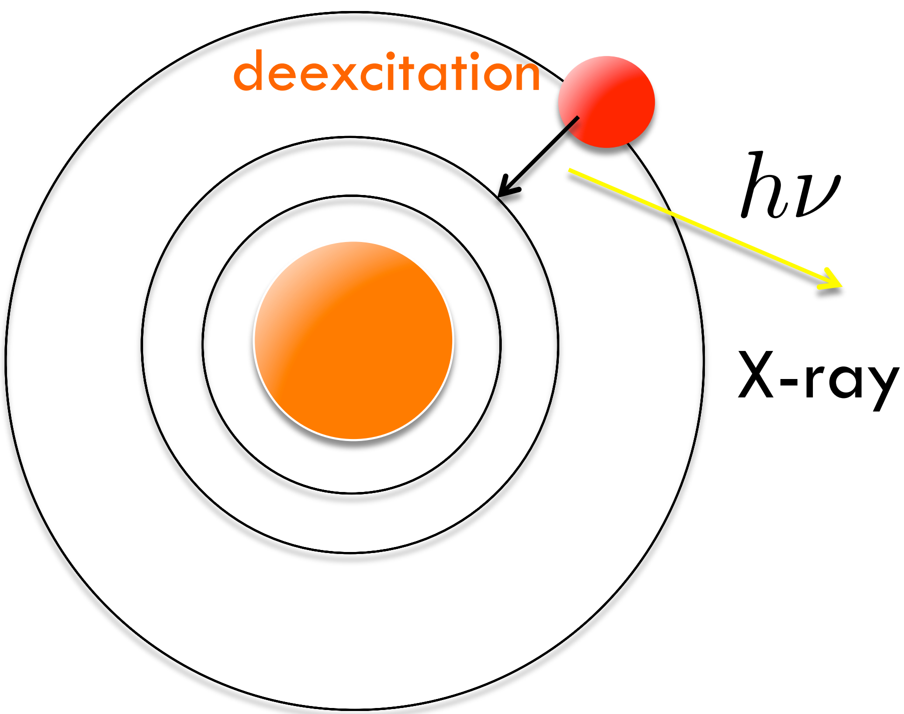
W. Weise, NPA553(93)59.

Chiral restoration at finite density can be studied

Conventional Method to Produce Pionic Atom

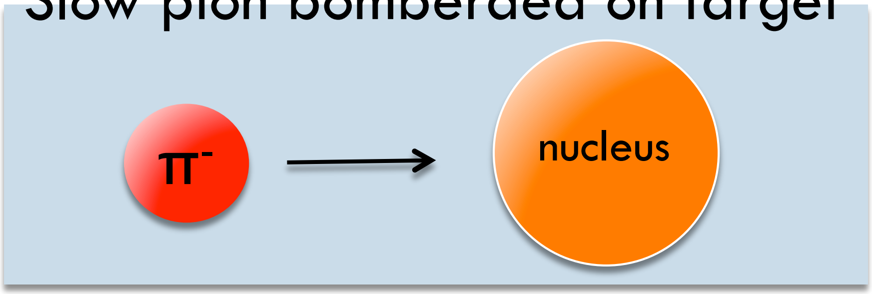
Slow pion bombarded on target

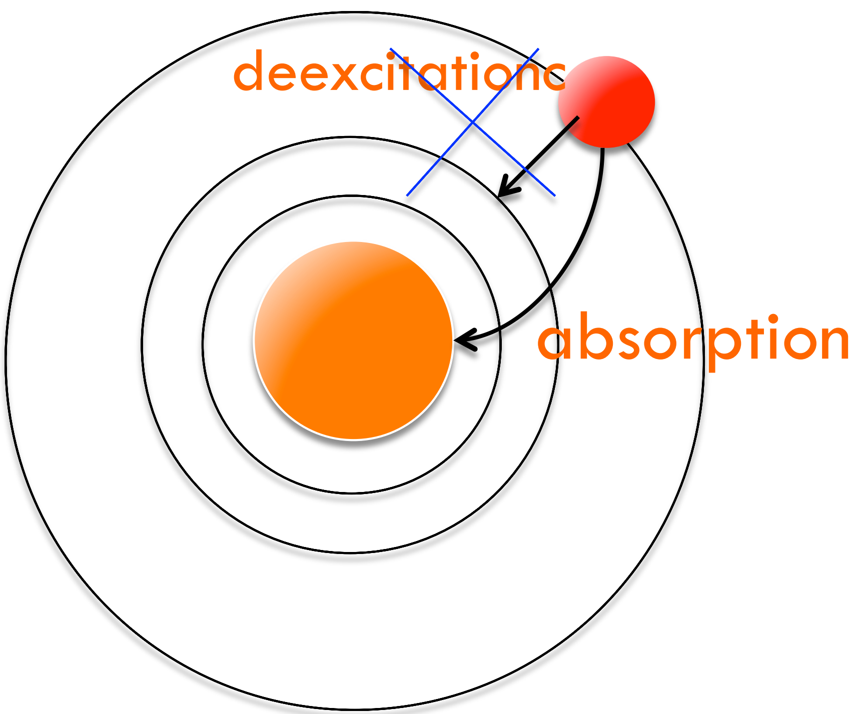




Conventional Method to Produce Pionic Atom

Slow pion bomberded on target





For heavy nuclei

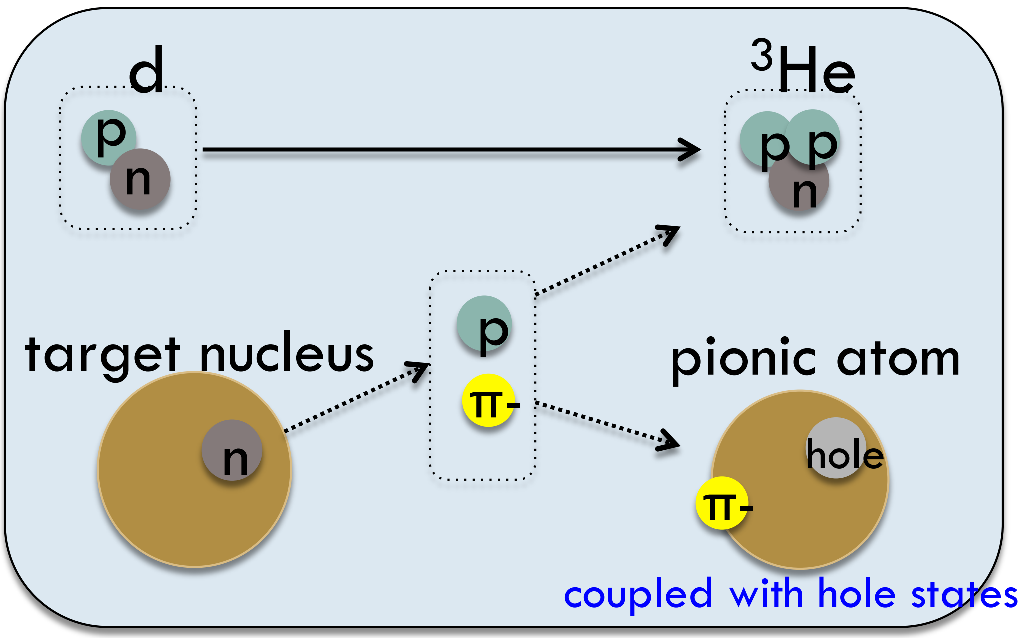
$$\Gamma_{abs} > \Gamma_{deex}$$

Pion is absorbed by the nucleus before they reach the deeply bound state.

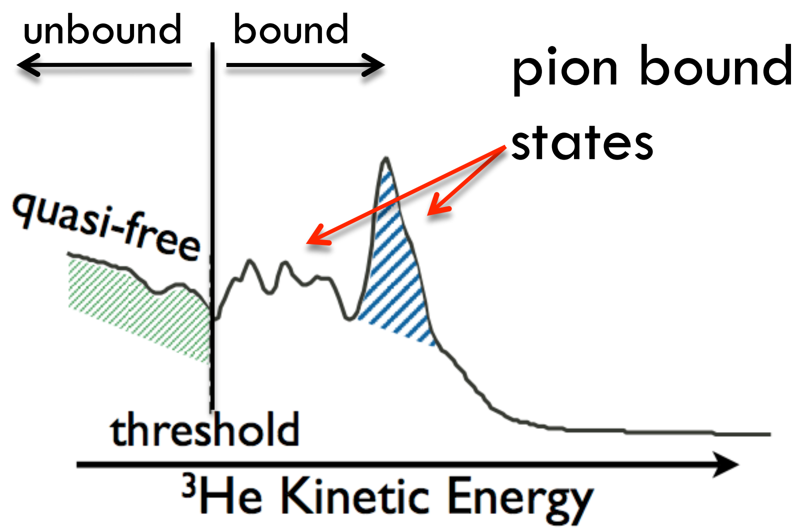
⬇

Little sensitivity to in medium properties

Missing-Mass Spectroscopy of (d,^{3}He) reaction



Expected ^{3}He spectrum

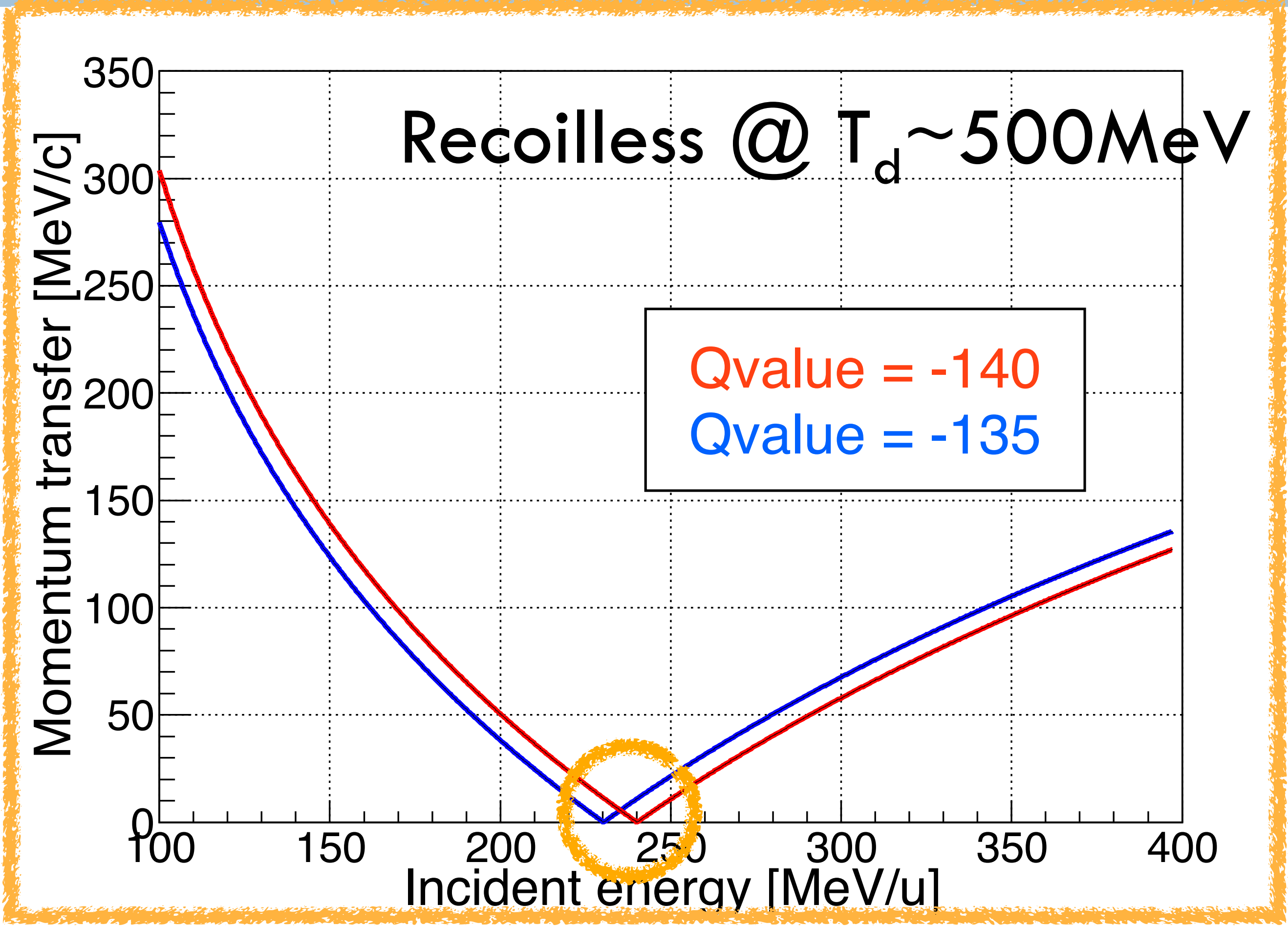


Missing-Mass spectroscopy

$$Q = (\ M_d + M_{122Sn}) - (\ M_{121Sn} + M_\pi - \underline{B.E._\pi} + M_{3He})$$
$$= T_{3He} + \underline{T_{piA}} - T_d$$

determined by momentum of ^{3}He

Missing-Mass Spectroscopy of (d,^{3}He) reaction



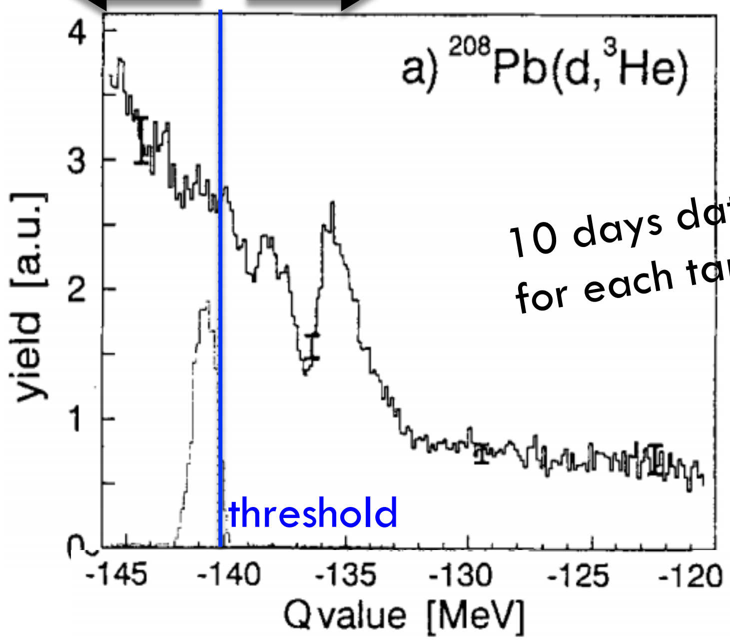
Small momentum transfer → small angular momentum transfer

s states are selectively populated

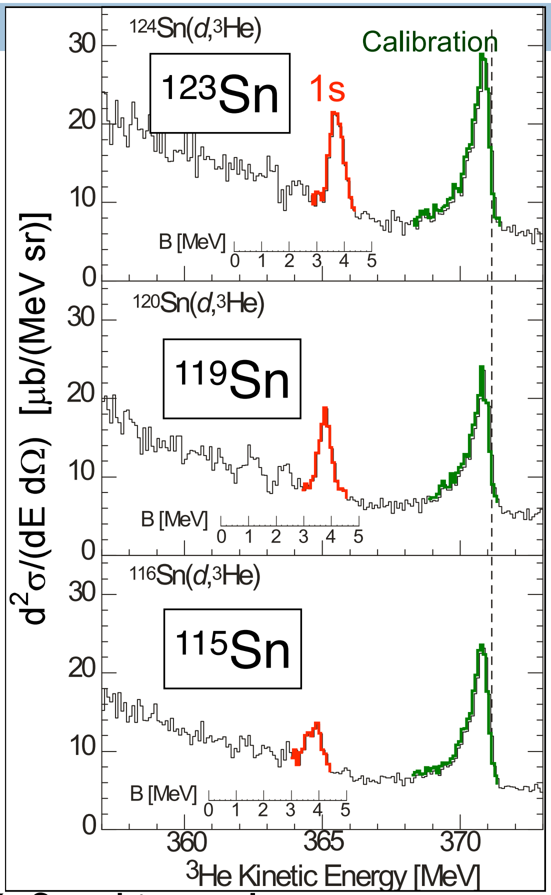
Previous Experiments at GSI

Unbound pion production

Bound region



10 days data-taking for each targets

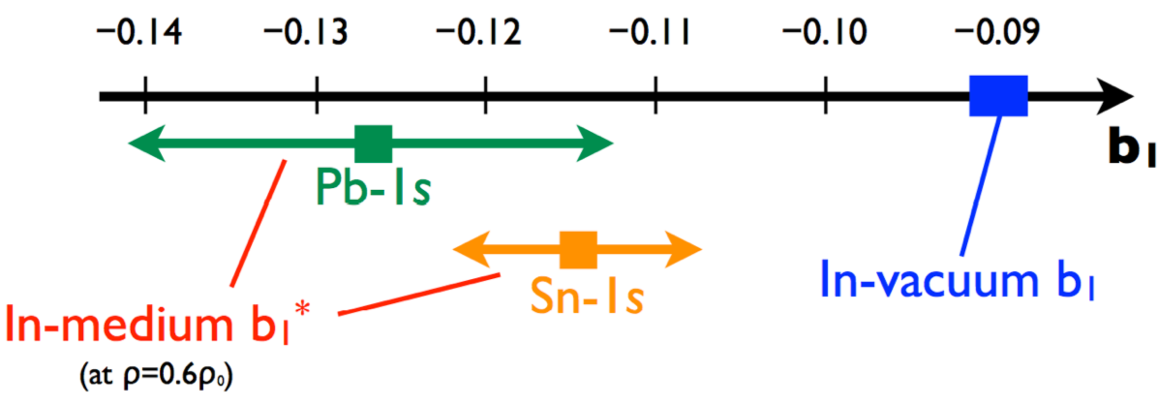


K. Itahashi, et al.,
Phys. Rev. C62 025202 (2000)

K. Suzuki, et al.,
Phys. Rev. Lett. 92, 072302 (2004)

Pionic atoms with Pb and Sn isotopes were observed.

Precision of b_1 in Previous Experiments with (d,^{3}He)



Large Errors!

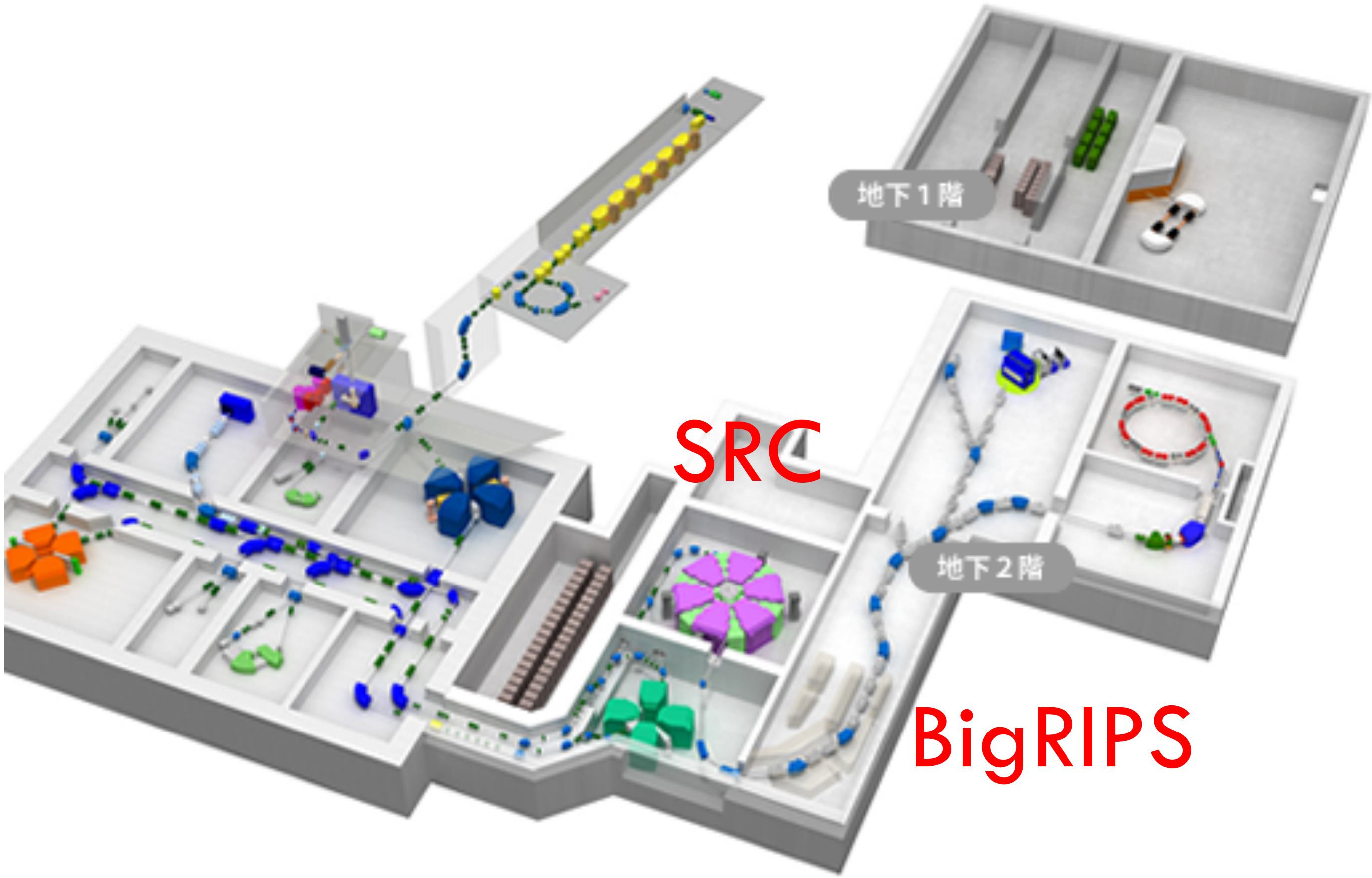
K. Suzuki et al., PRL92(04)072302.

$$\boxed{\frac{b_1^{\mathrm{free}}}{b_1} = 0.78 \pm 0.05} \longrightarrow \boxed{\frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle} \approx 0.66 \pm 0.06}$$

Chiral condensate is reduced by 35% at ρ_0

Experiment at RI Beam Factory

Experiment at RIBF



Intense d beam (10^{12}/s) is supplied by SRC

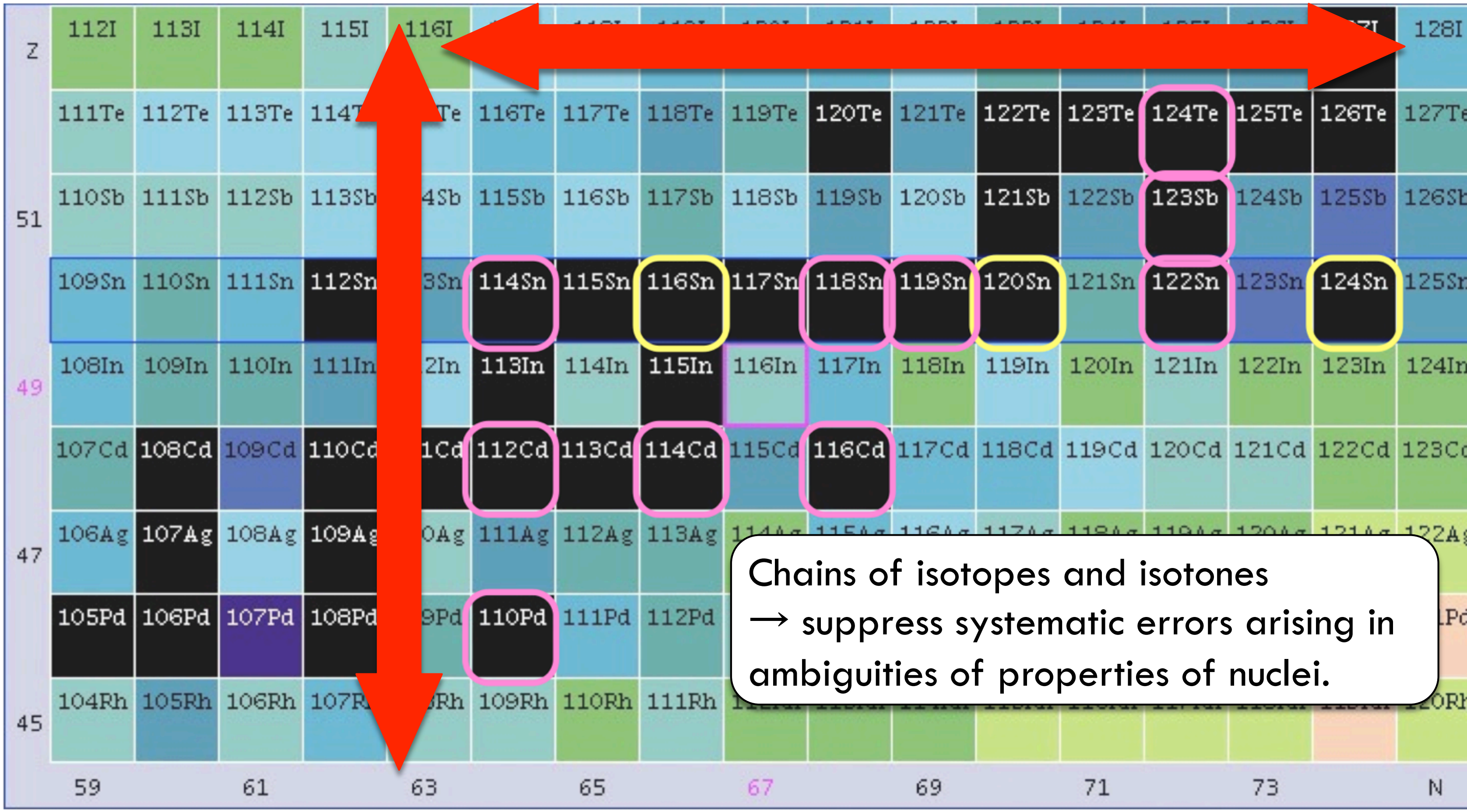
50 times stronger than GSI synchrotron

Systematic Study at RIBF

Measured at GSI

Systematic Study at RIBF

Isotopes and Isotones chain near Sn

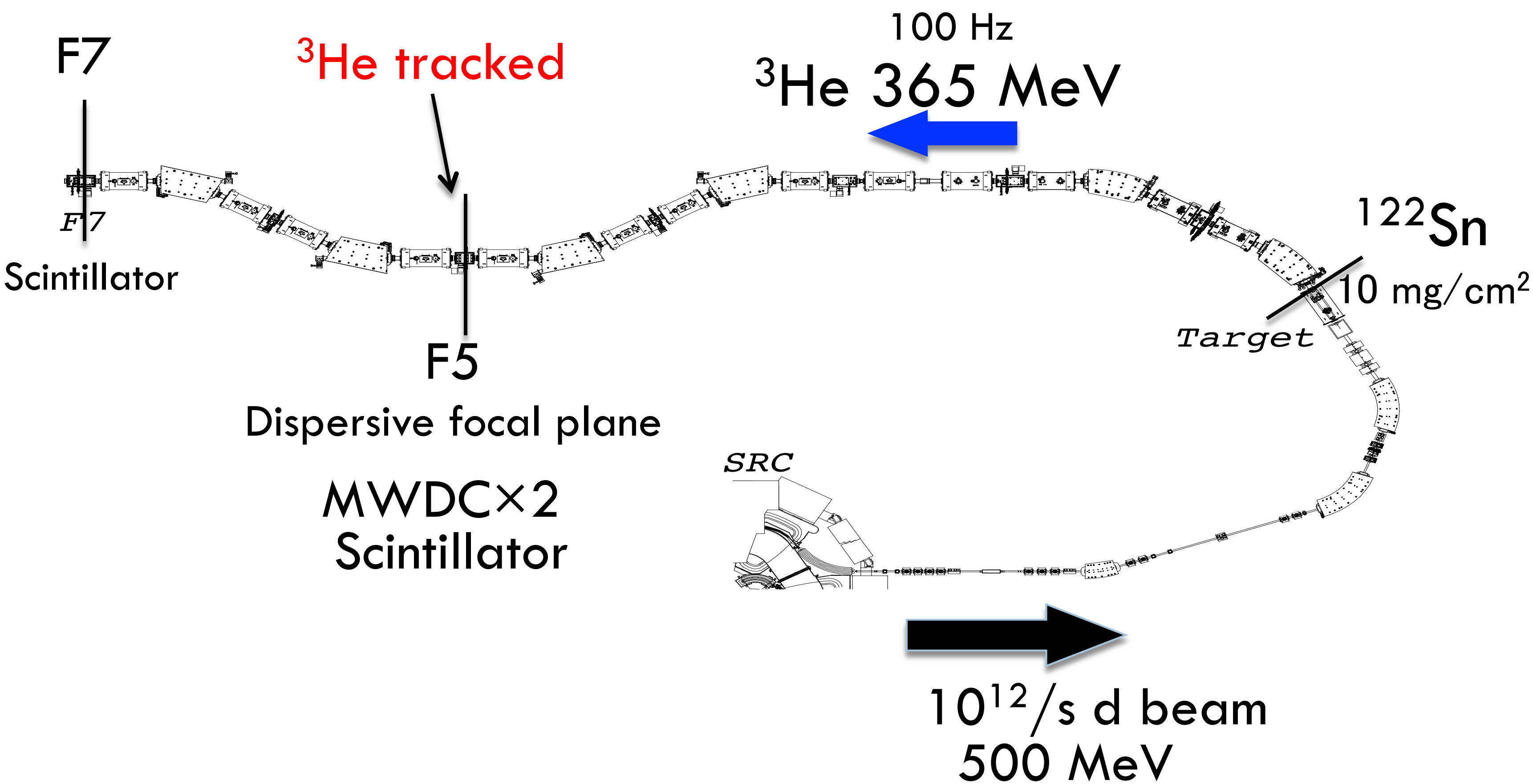


pionic atoms with isotopes and isotones near Sn

Systematic Study at RIBF

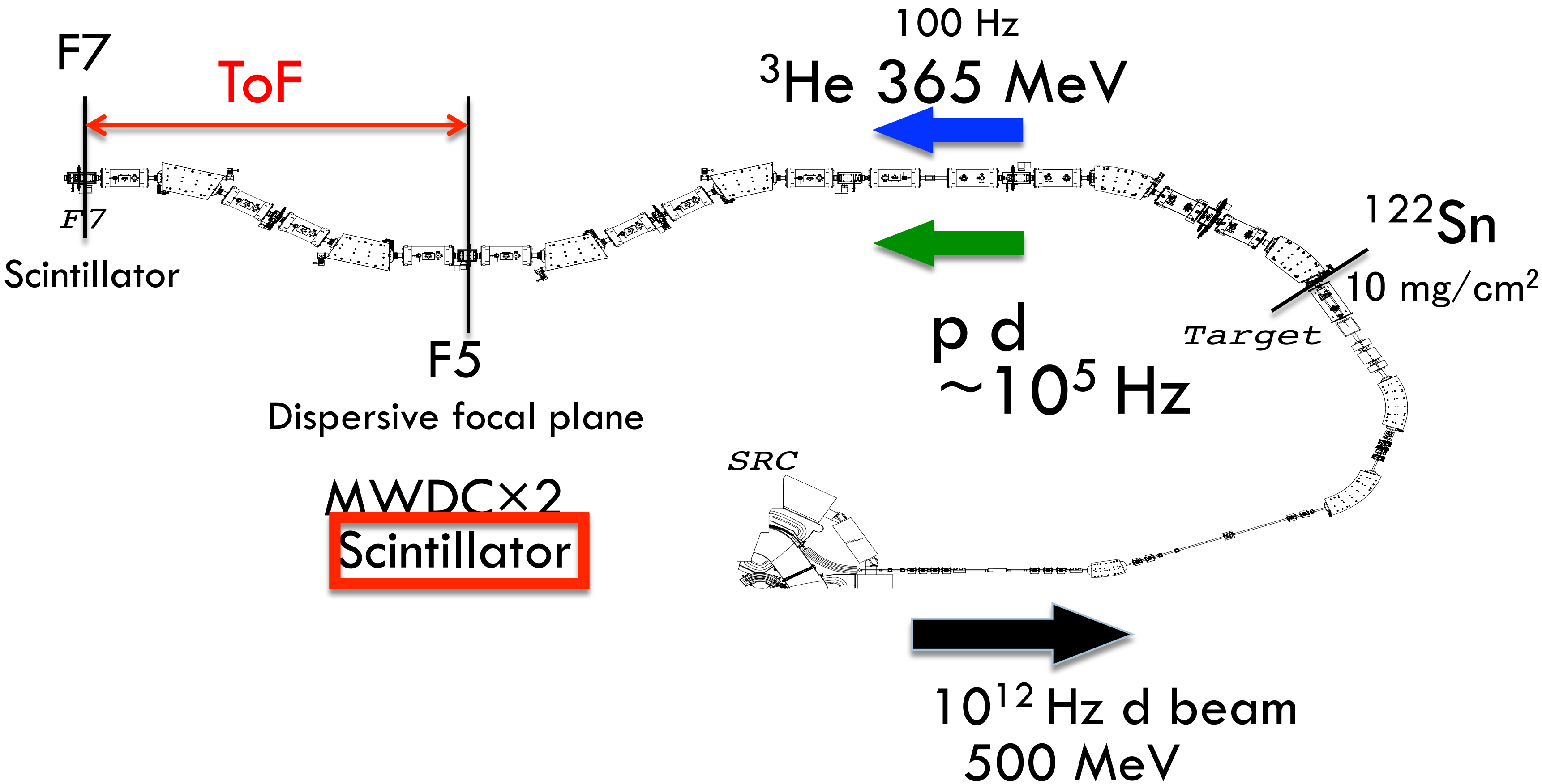
Target in Pilot Experiment

Experiment Setup: BigRIPS Spectrometer



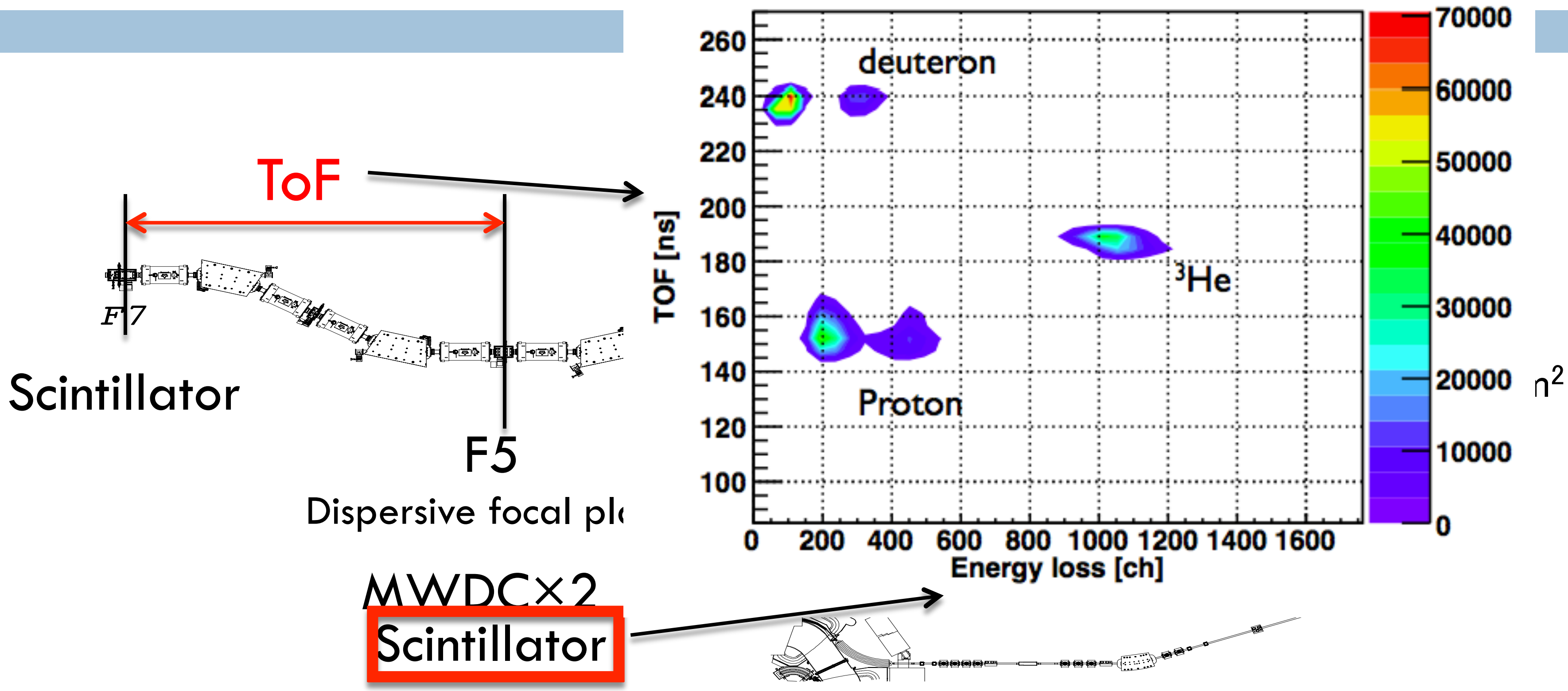
- ^{3}He position and angle are measured at F5 dispersive focal plane.

Particle Identification



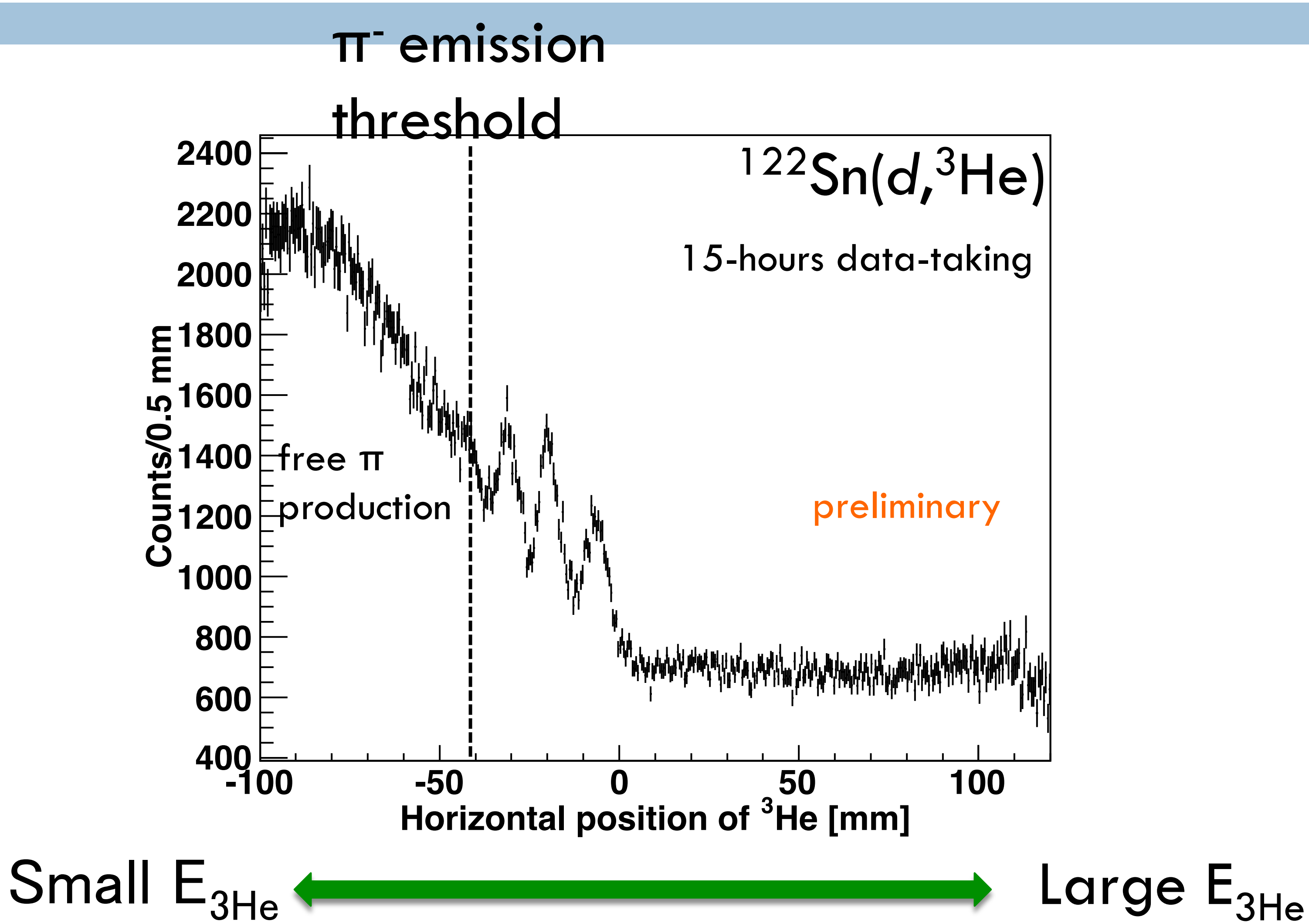
Background were identified by measuring ToF and ΔE

Particle Identification



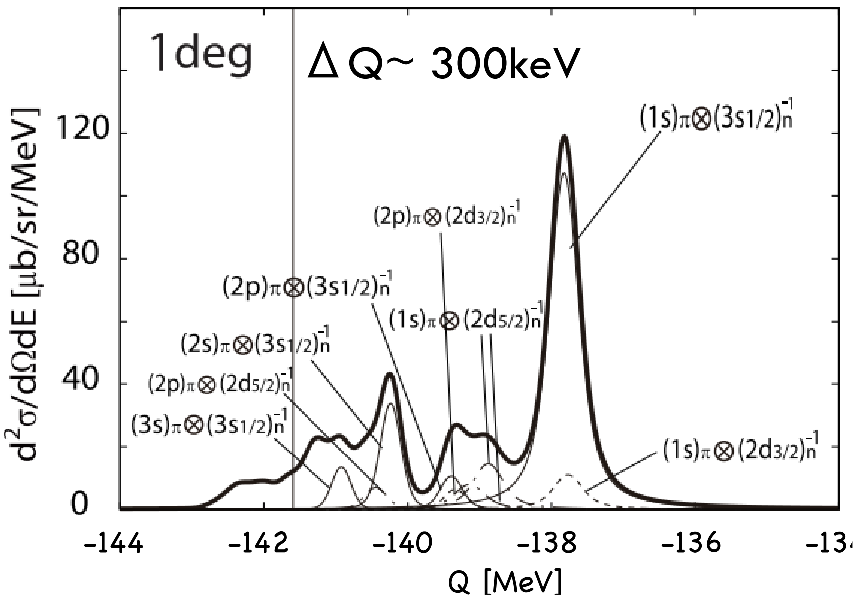
Background were identified by measuring Tof and ΔE

Pilot Experiment Result: ^{3}He Spectrum at F5

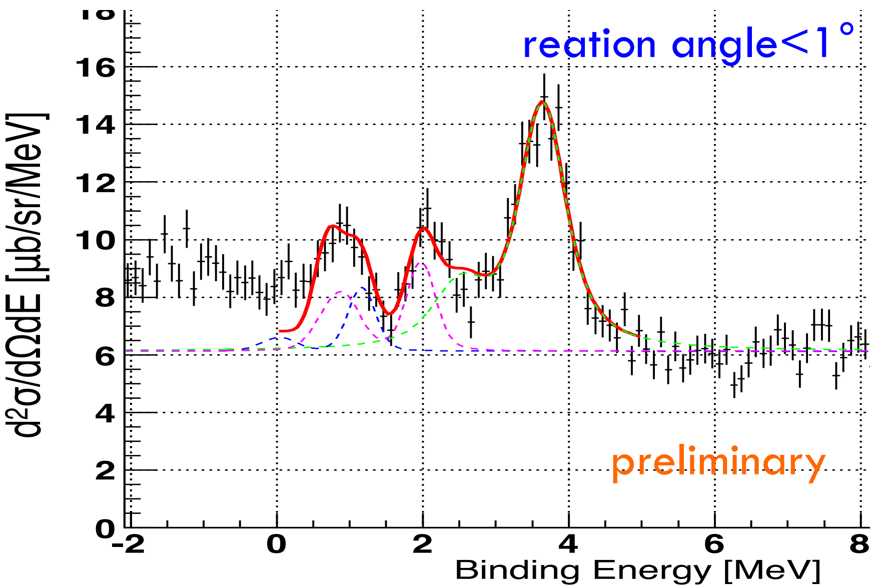


Pilot Experiment Result: Comparison to Theory

Theoretical spectrum



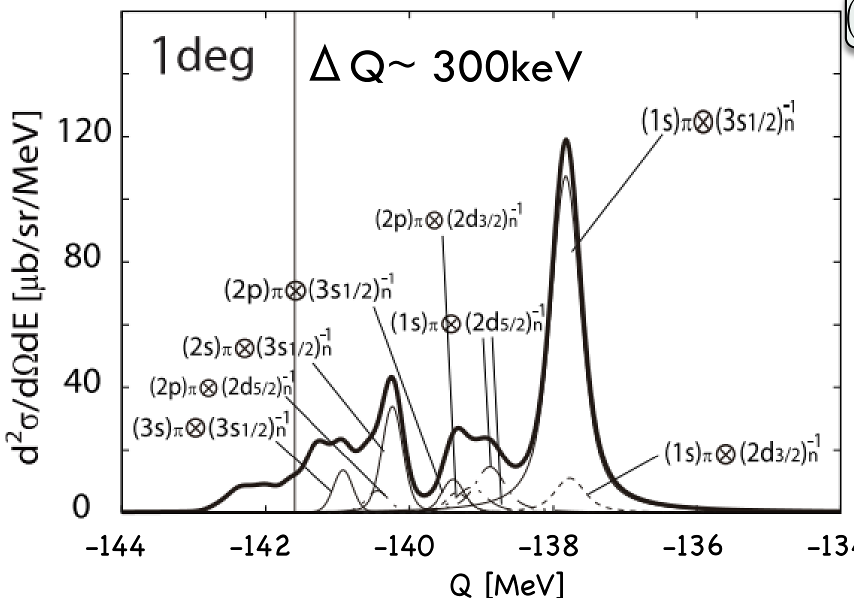
Experimental spectrum



*N. Ikeno et al., Eur. Phys. J. A 47, 161 (2011)

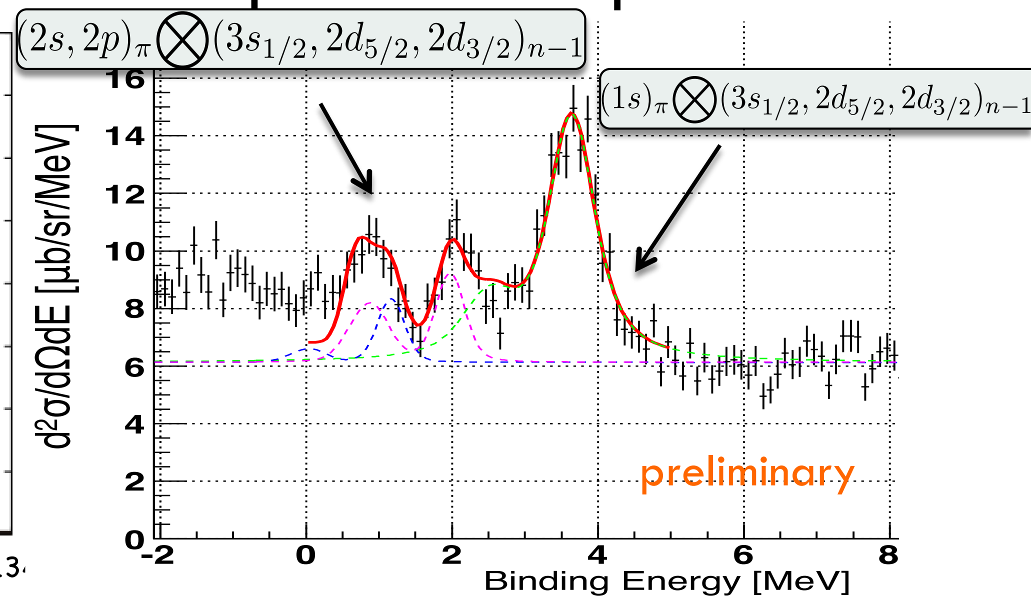
Pilot Experiment Result: Comparison to Theory

Theoretical spectrum



*N. Ikeno et al., Eur. Phys. J. A 47, 161 (2011)

Experimental spectrum



reation angle<1°

- Qualitatively good agreement.
- Pionic ^{121}Sn 1s, 2s, 2p states were observed for the first time

Analysis is ongoing…

Summary and Outlook of The First Half

Summary

・Spectroscopy of deeply bound pionic atoms reveals the restoration of chiral symmetry at finite density.

・We are conducting a systematic measurement of pionic atoms at RIBF.

・In the pilot experiment we succeeded in observing pionic atom of ^{121}Sn for the first time.

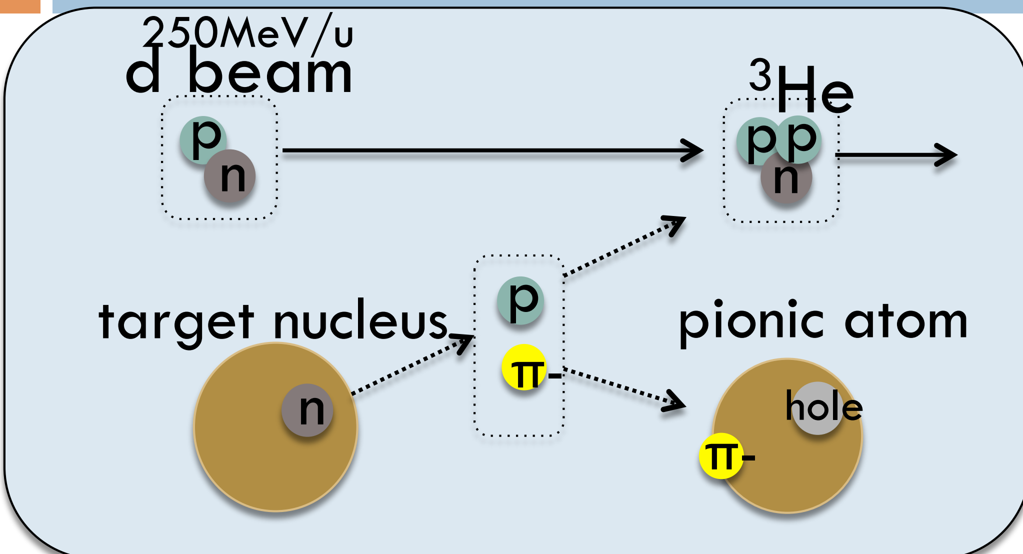
Outlook

・We are finalizing the analysis of the pilot experiment.

・We are preparing for main experiment, in which several targets are employed.

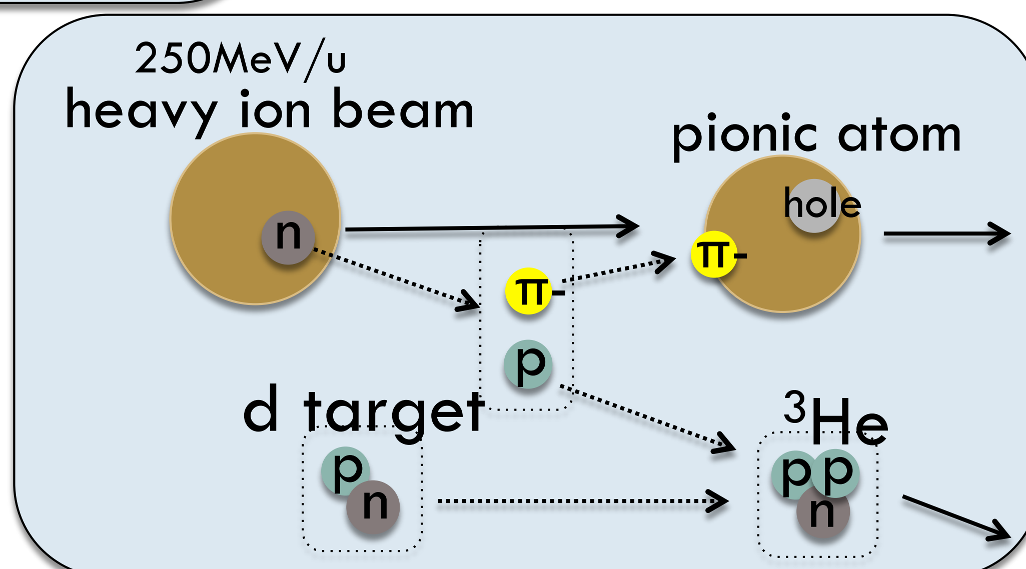
Future Plan
Spectroscopy with Inverse Kinematics

Experimental Method: Inverse Kinematics

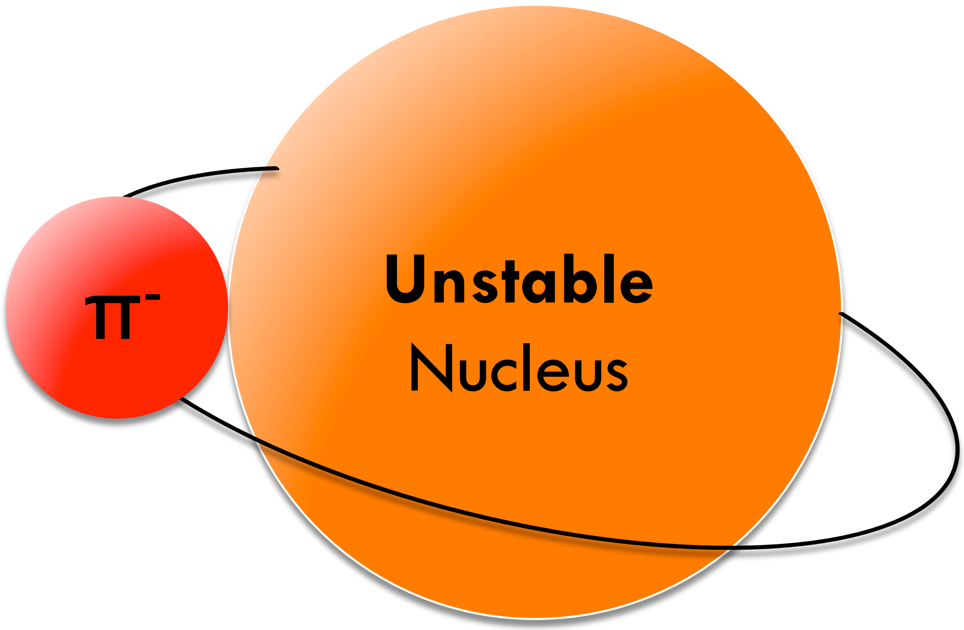


Normal Kinematics
Heavy ion: target
deuteron: beam

Inverse Kinematics
Heavy ion: beam
Deuteron: target

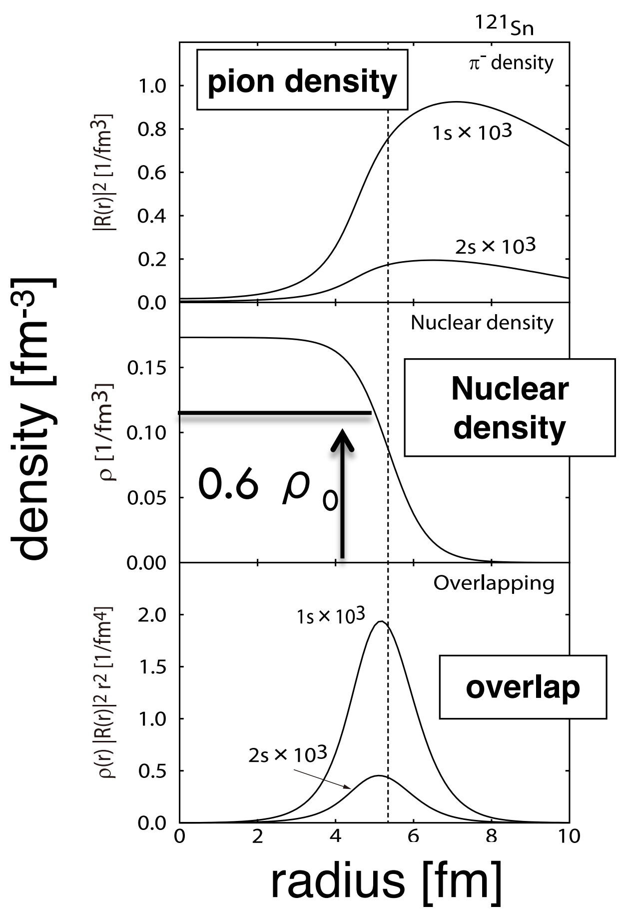


Pionic Atom with Unstable Nuclei



Pion is bound by an unstable nucleus

Pionic Atom with Stable Nuclei

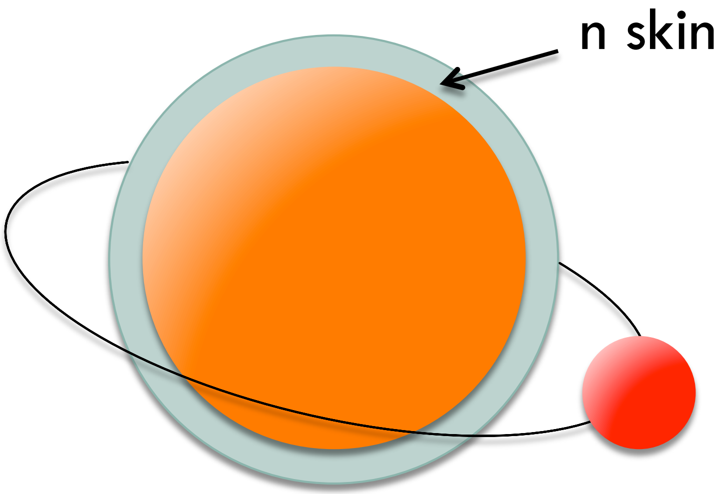


N. Ikeno *et al.*, PTP126(2011)483.

Density which pion probes is about 0.6 ρ_0 regardless of the nuclear species or pion orbits

Only $\langle|\bar{q}q|\rangle$ around 0.6 ρ_0 is evaluated by pionic atoms with stable nuclei

Physics Motivation: Pionic Atom with Unstable Nuclei

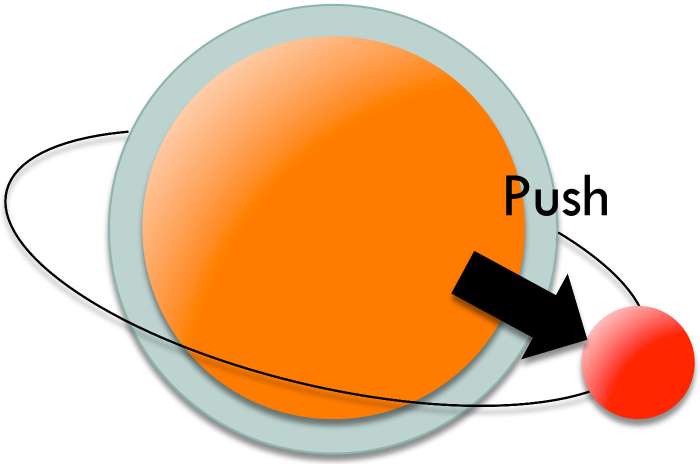


Pion-Nucleus Interaction

$$V_{s-wave} = b_0\rho + \underline{b_1(\rho_n} - \rho_p) + B_0\rho^2$$

Neutron-Pion: Repulsive!

Physics Motivation: Pionic Atom with Unstable Nuclei



Pion-Neucleus Interaction

$$V_{s-wave} = b_0\rho + \underline{b_1(\rho_n} - \rho_p) + B_0\rho^2$$

Neutron-Pion: Repulsive!

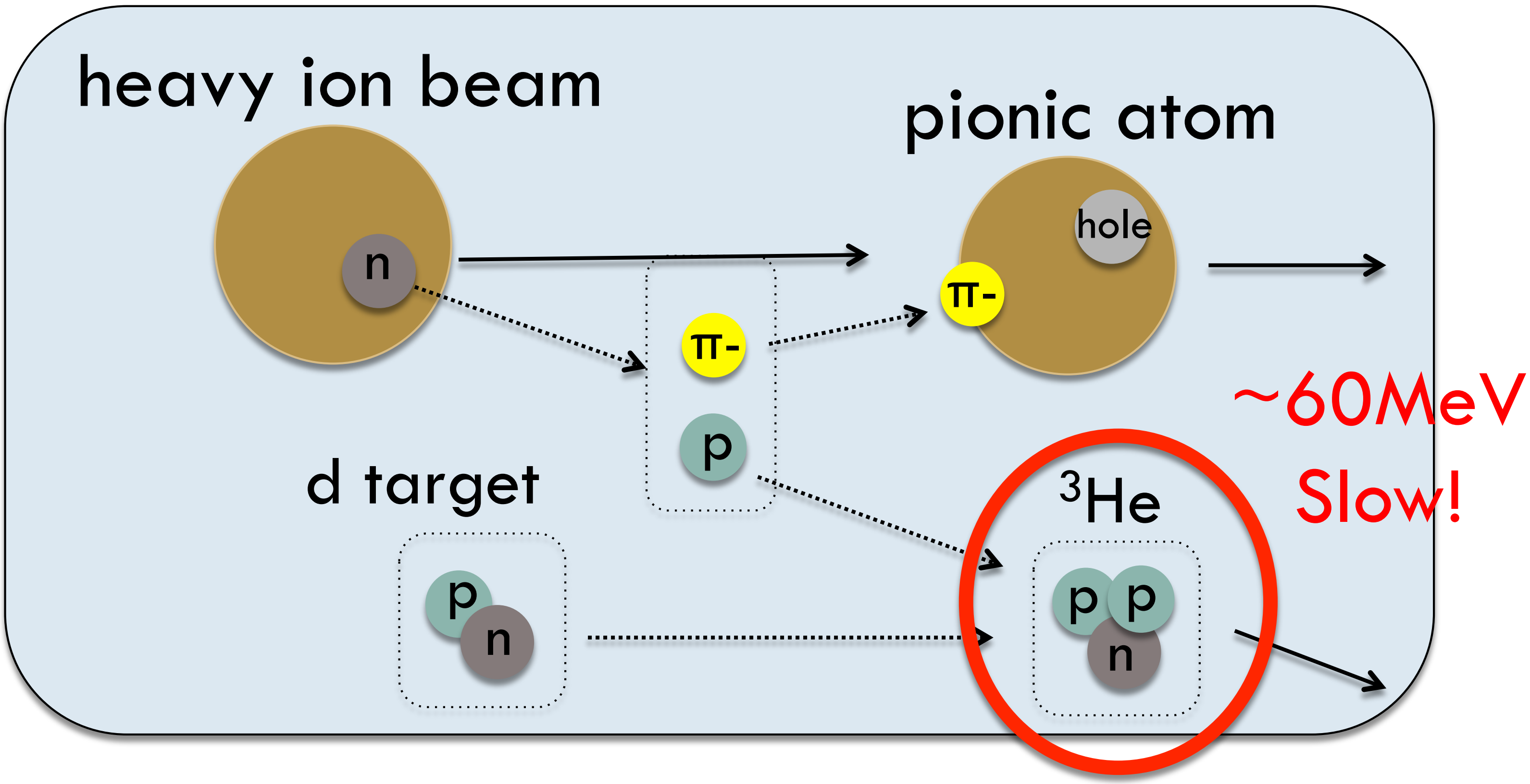
Pion is pushed outward

Different density lower than 0.6 ρ_0 is probed

⬇

Density dependence of $|\langle\overline{q}q\rangle|$ will be deduced

Experimental Method: Inverse Kinematics

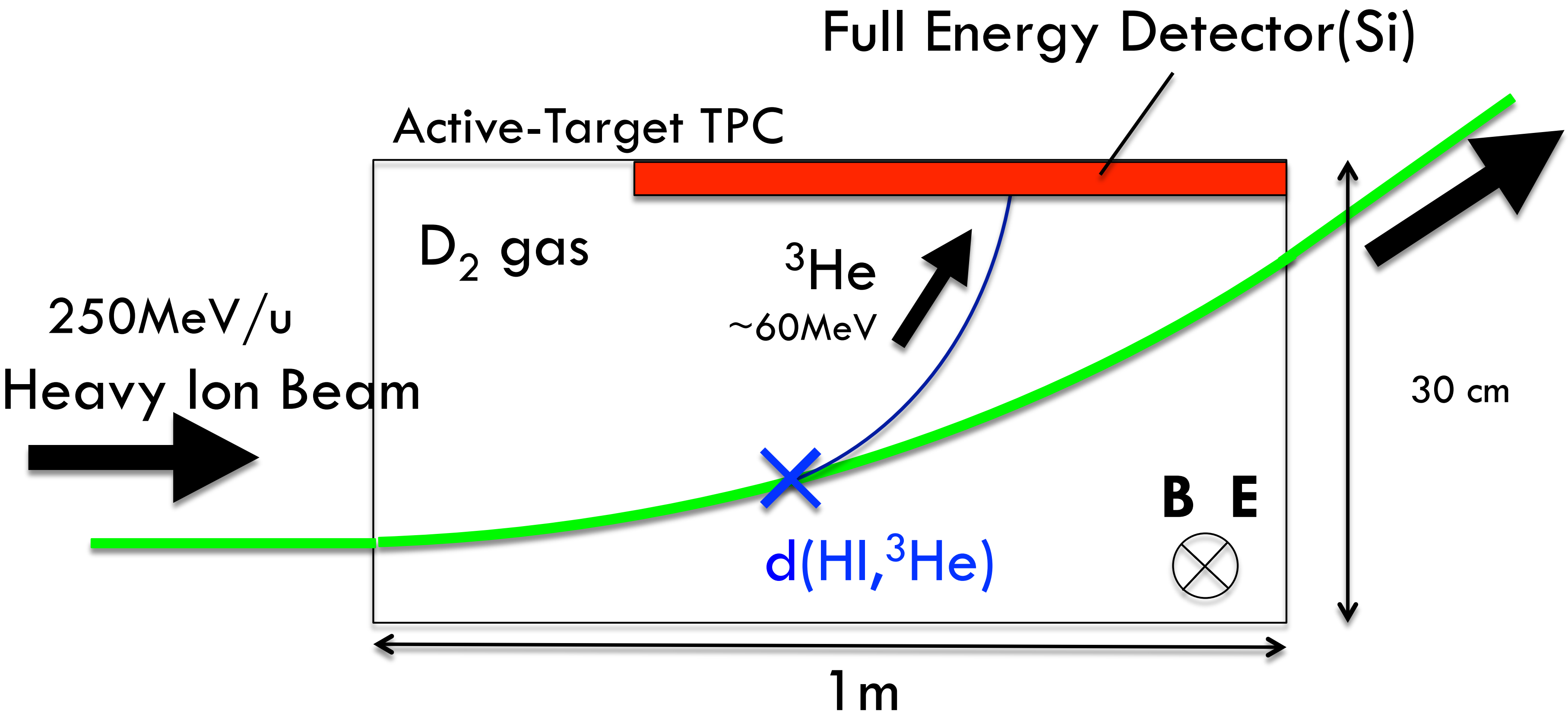


Momentum of ^{3}He should be determined precisely

$\Delta p/p \sim 0.1\%$

Experimental Setup and Method for Inverse Kinematics

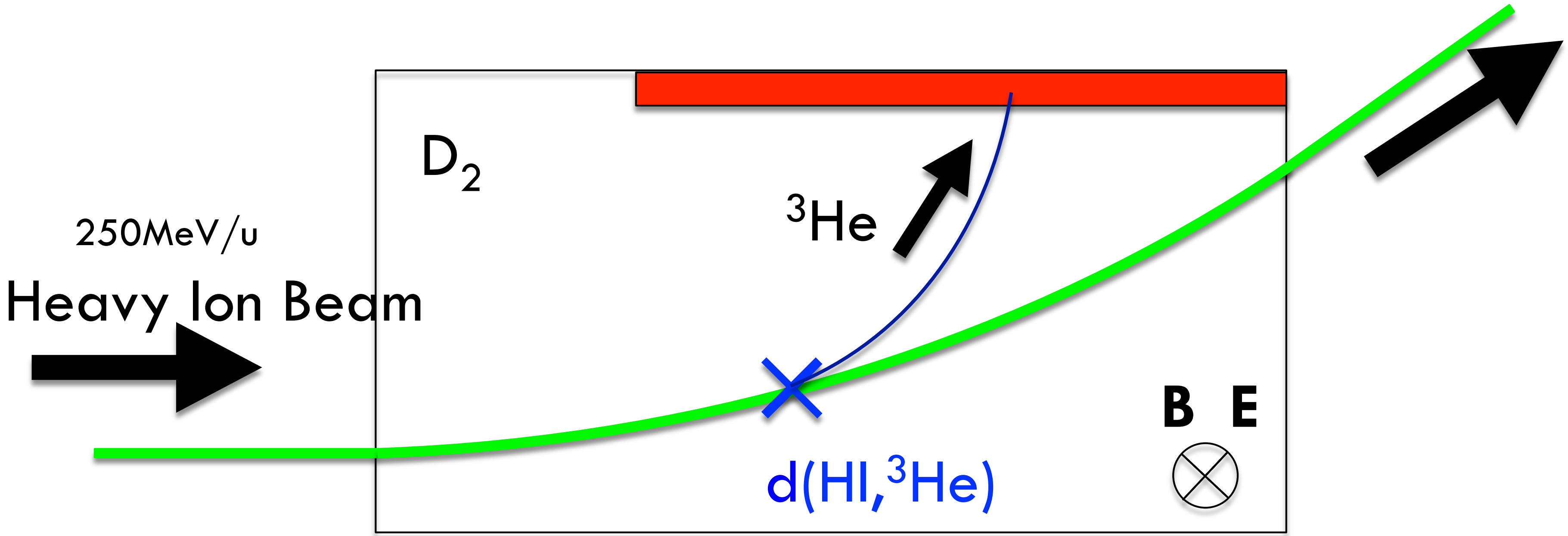
Conceptual Design: Active Target TPC



Active Target TPC + Full Energy Detector

Track of beam and recoil He are measured.

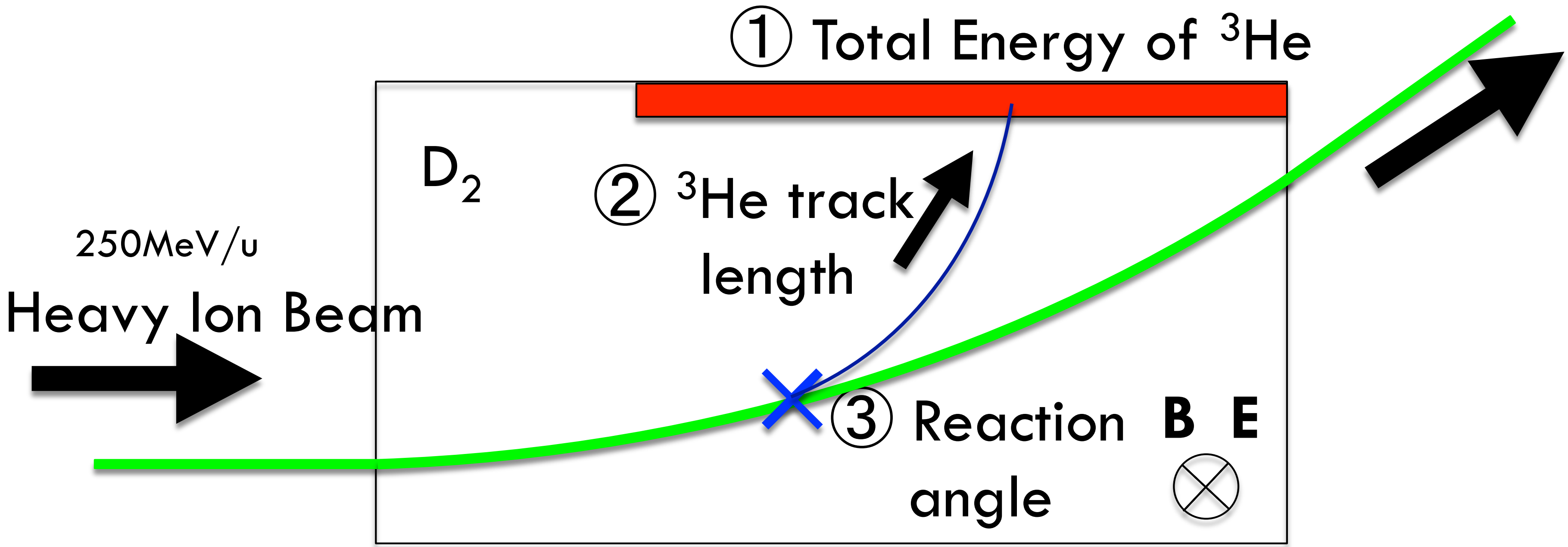
Experimental Method: Missing-Mass Measurement



For the missing-mass measurement,

- kinetic energy of the incident beam ← Known
- momentum of ^{3}He at reaction point ← Should be measured

Experimental Method: Missing-Mass Measurement



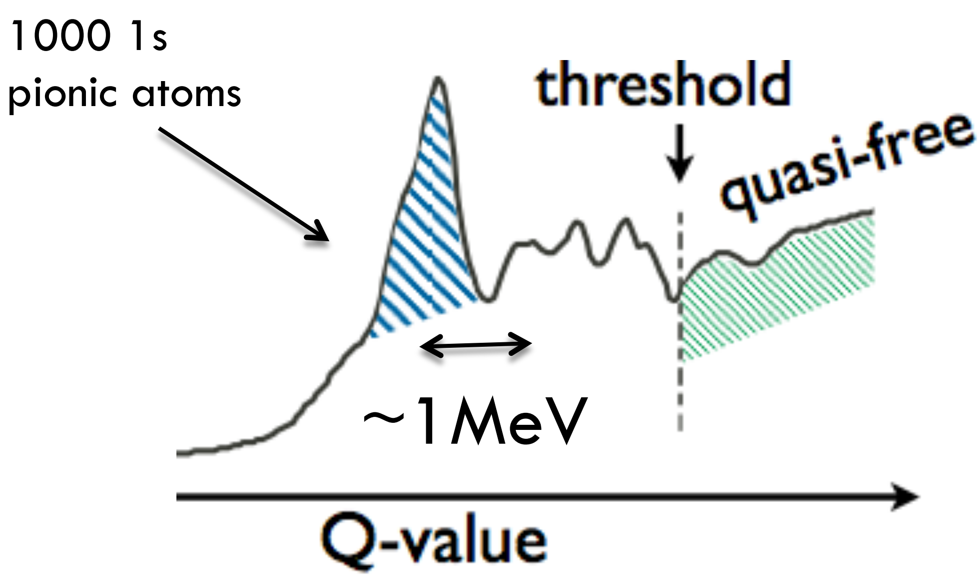
① ^{3}He energy is measured at Si
② ΔE deduced from track length
③ θ deduced from track

→ p_{3He} at reaction point

Resolution and Yield Estimation

Goal of Resolution and yield

Resolution	ΔQ(FWHM) < 1MeV
Yield	10^2/day (for 1s state)



・Peak spacing is about 1MeV
・comparable yield with normal kinematics for 10 days data-taking

Goal of Resolution and yield

Resolution	ΔQ(FWHM) < 1MeV
Yield	10^2/day (for 1s state)

Conditions of the estimation

TPC position resolution ~500 μm
Si detector energy resolution ~ 0.1%(σ)

Assuming 10^6 /s beam ← Limit of the detector

Resolution

Cause	ΔQ (FWHM) [keV]
Energy Resolution of Si at $T_{He} \sim 60$ MeV $\sigma_{Si} = 0.1$ %	
Energy Straggling of ^{3}He in TPC	
Vertex Reconstruction With Incident Beam $\sigma_{TPC} = 500$ μm	
Total	

Resolution

Cause	ΔQ (FWHM) [keV]
Energy Resolution of Si at T_{He} ~ 60 MeV σ_{Si} = 0.1 %	~ 350
Energy Straggling of ^{3}He in TPC	~ 350
Vertex Reconstruction With Incident Beam σ_{TPC} = 500 μm	~ 130
Total	**~ 500**

Yield Estimation

Target	D_2 gas (1 atm, 293.15 K) 100 cm
Beam Intensity [/s]	1×10^{6}
Cross Section [μb]	2.54×10^{-1}
Yield [/day]	**1.1×10^{2}**

Conceptual design fulfills requirement

Resolution	Δ Q(FWHM) ~ 500keV
Yield	$1.1*10^2$/day (for 1s state)

We can attain sufficient yield and reoslution with active target TPC

Test of Silicon detectors

We have started to develop the detector
now testing the silicon detector

Summary

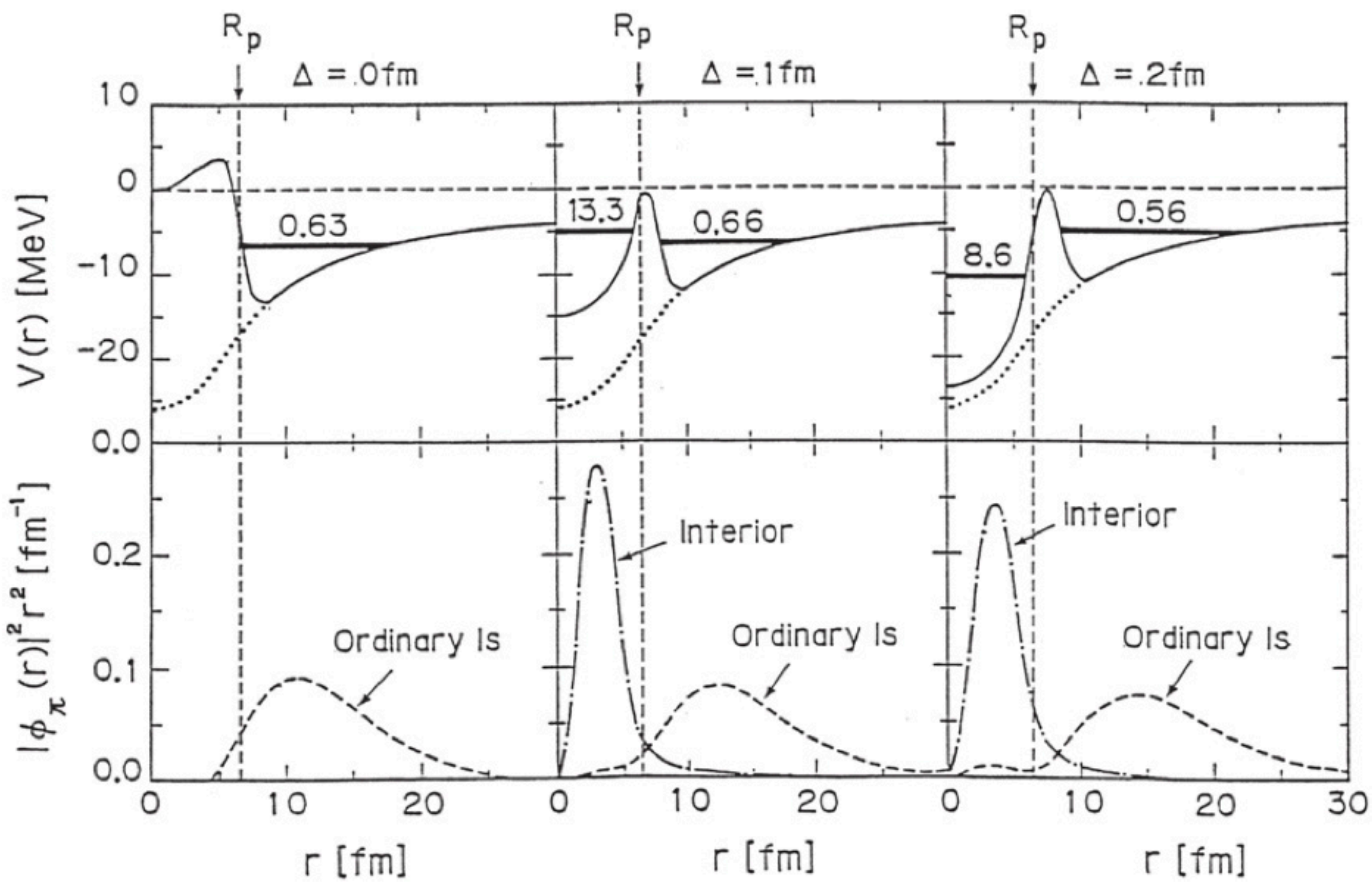
- We are conducting a systematic measurement of pionic atoms at RIBF

- In the pilot experiment we succeeded in observing pionic atoms of ^{121}Sn for the first time

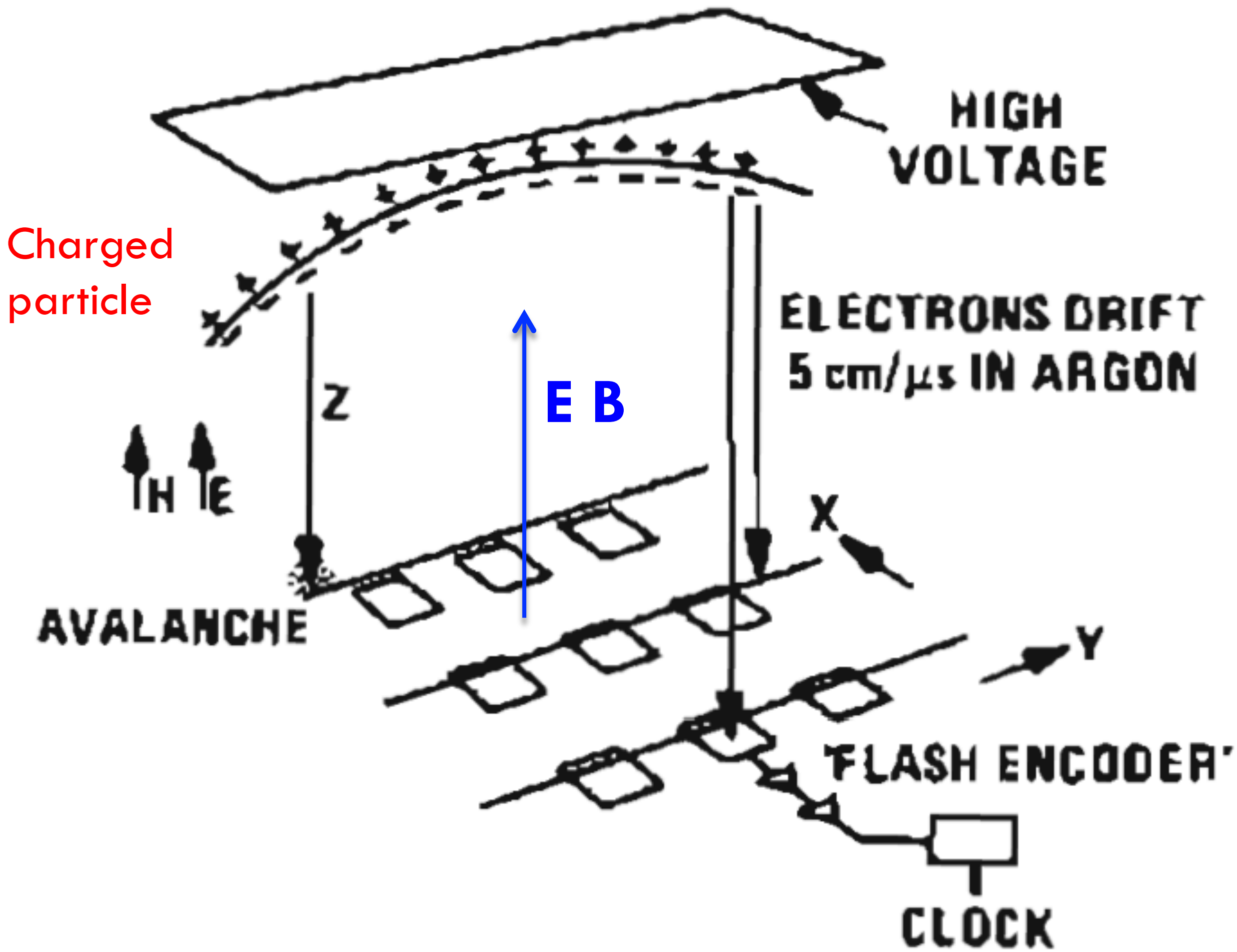
- We are planning for the spectroscopy of pionic atoms with inverse kinematics.

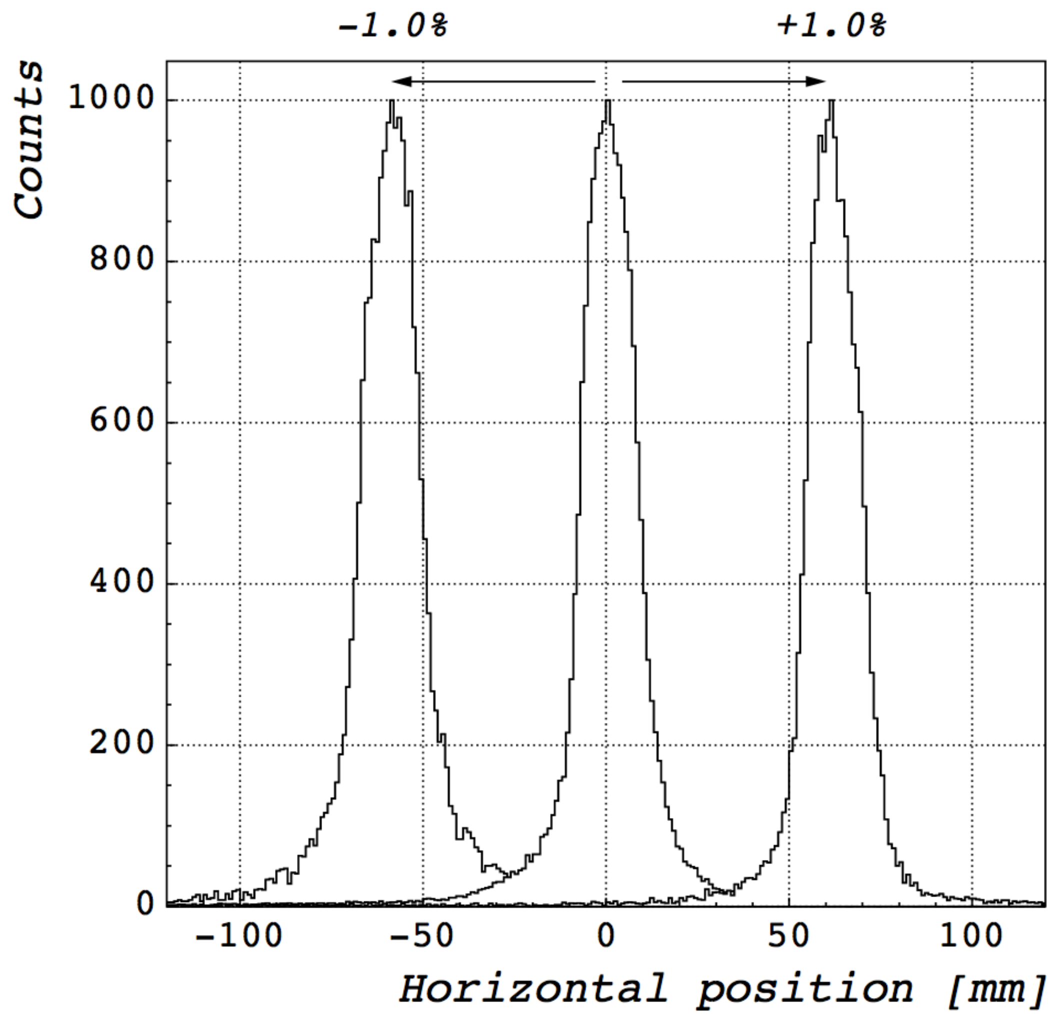
- Spectroscopy by inverse kinematics is feasible with active-target TPC

Sensitivity to Neutron Skin



TPC


HIGH VOLTAGE
Charged particle
ELECTRONS DRIFT
5 cm/μs IN ARGON
Z
E B
H
E
X
Y
AVALANCHE
'FLASH ENCODER'
CLOCK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Horizontal position [mm]